

Controlling Carburizing for Top Quality Gears

Roy F. Kern
Kern Engineering Company,
Peoria, IL

A carburized alloy steel gear has the greatest load-carrying capacity, but only if it is heat treated properly. For high quality carburizing, the case depth, case microstructure, and case hardness must be controlled carefully.

The depth of penetration of carbon into a gear tooth is a function of carbon potential of the atmosphere, temperature, time, and composition of the steel. Problems with the production carburizing of parts start with the question: How and where is case depth to be measured?

Many gear drawings and/or carburize specifications require that the case depth be the distance inward, measured normal to the tooth flanks where a certain hardness occurs. Universally, the depth is measured as that distance to where a hardness of 50 Rockwell C occurs. The most significant test location is at the lowest point of single tooth contact (LPSTC) midway between the ends of the teeth.

This is much more complicated than carbon penetration because this hardness is affected not only by the carbon content of the steel, but also by its hardenability, the mass of the tooth, and, of course, the vigor of the quench.

The first step in case depth control is to make sure that the gear's mass, the hardenability of the steel in the gear, and the quench available indicate that there is a possibility to meet the case depth requirements. The most difficult part of this process is to estimate the vigor of the quench. This is done using the Jominy end-quench specimen showing in Fig. 1.

The upper left-hand corner of Fig. 1 shows how an end-quench test is performed.

The specimen is heated to a hardening temperature and then quenched on one end with water. The closer to the end, the more drastic the quench is, and the harder the steel becomes, as seen in the twice-scale drawing at the bottom of the figure.

Note that at 1/16" from the quenched end, the hardness is 45 Rockwell C. At 3/16" it is 41

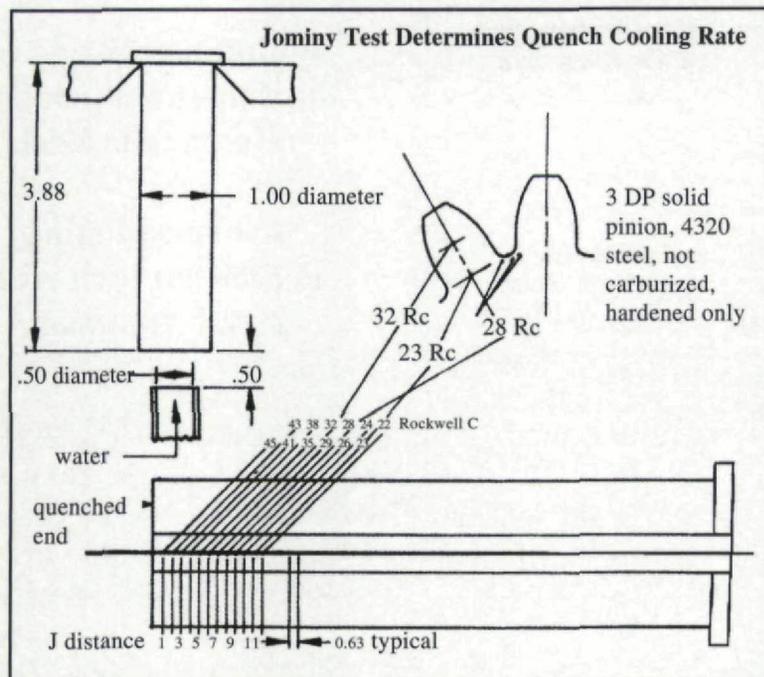


Fig. 1 - The upper left-hand corner of the figure shows how an end-quench test is performed with the Jominy end-quench specimen. One of the most difficult parts of case depth control is estimating the vigor of the quench.

Rockwell C, and at 6/16" it is 32 Rockwell C. If a 3 DP solid pinion were made from this same steel, the core hardness at the pitch line would be 32 Rockwell C, so the quench cooling rate at the pitch line would be equal to 6/16" on the Jominy test specimen - commonly referred to as J6. In the root fillet, the gear would have hardened to only 28 Rockwell C, which is approximate J8. This has been done for both web-type gears and solid pinions, as shown in Fig. 2, and for round bars, as shown in Fig. 3.

For example, Fig. 2 shows that the quench cooling rate in the root fillet of a 4 DP solid pinion with an agitated oil quench corresponds to 6/16J or J6. The root fillet was chosen because it is close to the LPSTC, and its quench-cooling rate is quite similar.

For 9310 Steel, Fig. 4 shows all that is needed at the required case depth (to 50 Rockwell C) is 0.30% carbon. So if 0.060" case depth is required, the carburized depth to 0.30% carbon should be 0.060 plus approximately 0.010" or 0.070". This also is true of steels, such as 3310, 4820, and EX-55.

Lean Alloys

With steels, such as 8620H and other lean alloys, close control of case depth becomes much more difficult. This is because the hardening qualities of these steels vary widely with the manufacturer.

The 4 DP solid pinion in Fig. 4 shows that from 0.45% to more than 0.60% carbon is required at the specified depth below the surface, depending on steel source, to harden to 50 Rockwell C. This variation is so great that for precise control of case depth the heat treater should run suitable carburizing tests on samples from each heat of steel before running parts.

Beyond the hardenability of the steel, an important factor in the control of case depth is the use of a sample whose surface quench-cooling rate is the same as that at the test location on the gear, for example, at the LPSTC or in the root fillet. Because there are quench cooling rates in the root fillets for different types and pitches of gears and for different size rounds, heat treaters can plot the equivalents.

This is important because it often is economically impractical to cut a gear to check case depth. Fig. 5 shows a suggested sample design and table of sizes for different size gears.

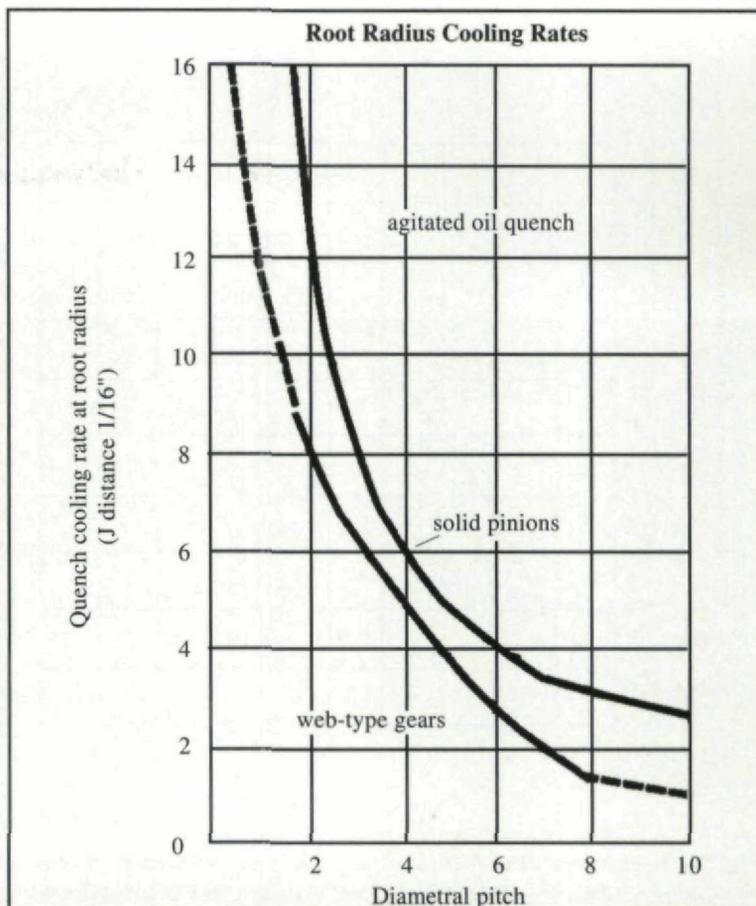


Fig. 2 - The quench cooling rate in the root fillet of a 4 DP solid pinion with an agitated oil quench corresponds to 6/16J or J6.

Unless otherwise specified, the case depth is determined by carefully cutting a 0.25"-thick transverse slice from the sample's center. The slice is further reduced in size so it can be polished to a suitable microscopic finish. The hardness probe then is run from the surface through the carburized case, using a graduated stage with the first reading at 0.001" and the balance at 0.005" steps. Either a Knoop or Vickers hardness tester is satisfactory.

The vigor of the quench also influences the case depth, and yet tests and surveys have shown that this important factor has received little attention in gear hardening.

Temperature Dependency

Case depth depends on the temperature at which the operation is carried out. There are three factors to keep in mind regarding the effect of temperature on case depth:

- The furnace thermocouple must indicate the temperature of the work.
- The furnace thermocouple performance must be traceable to at least a secondary master standard calibrated by the National Bureau of Standards.

Roy F. Kern

is president of Kern Engineering Co., a design and materials engineering firm. He is an active member of the American Society for Metals and the author of numerous books and papers, including *Selecting Steels for Heat Treatment and Steel Selection* with M. Suess for John Wiley and Sons, New York.

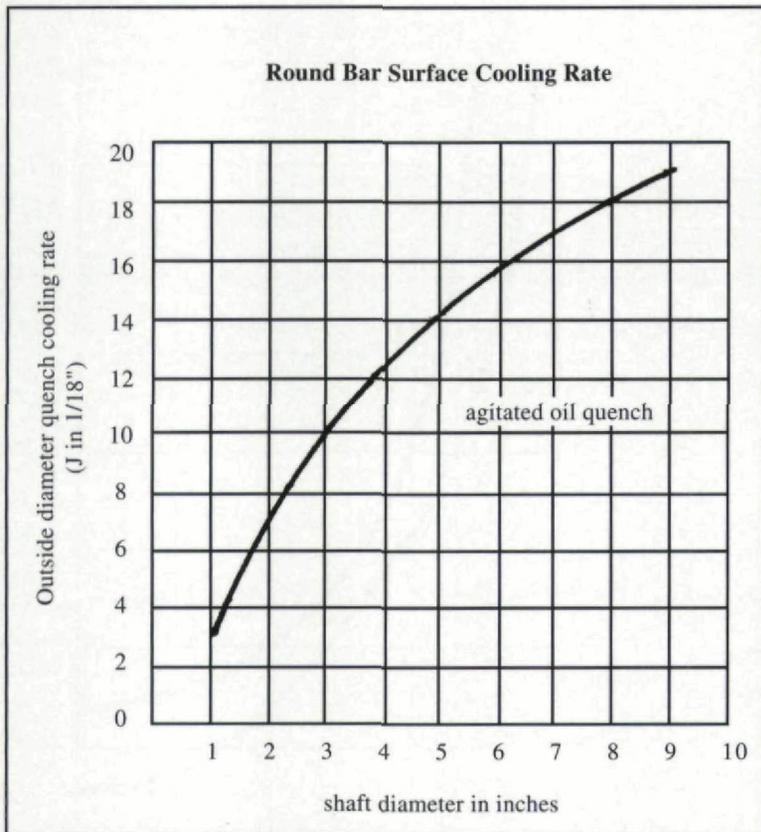


Fig. 3 - In the root fillet of round bars, the gear hardened to only 28 Rockwell C, which is approximately J8. Surface outside diameter cooling rate is expressed as J distance of round bars quenched in agitated oil.

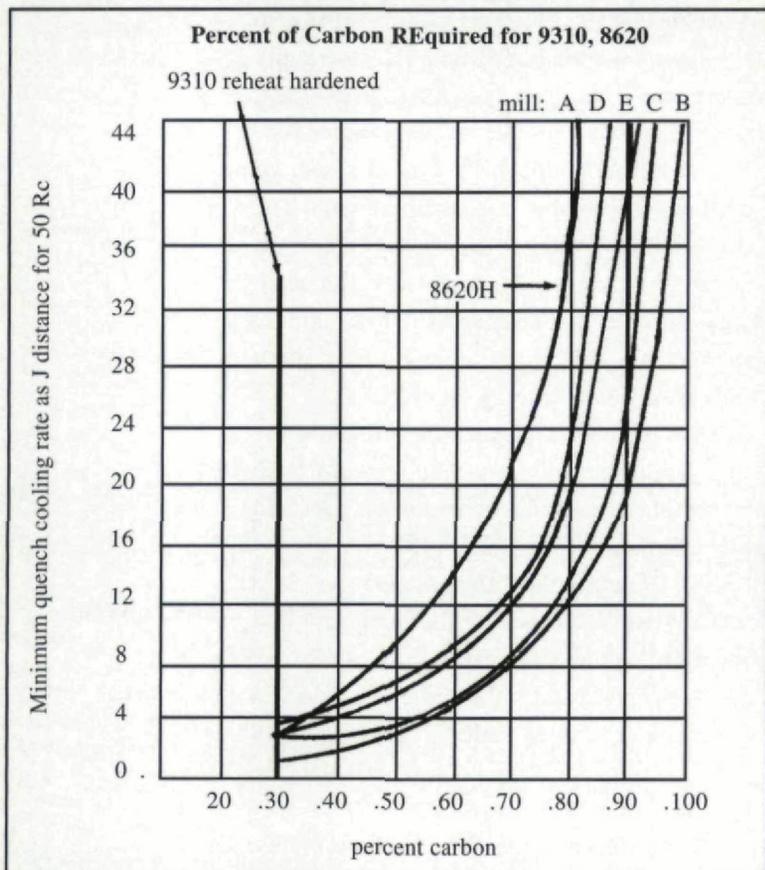


Fig. 4 - With 9310 steel, all that is needed at the required case depth - to 50 Rockwell C - is 0.30% carbon. Depending on manufacturer, 8620 steel requires much more carbon.

- The temperature control device must be operating properly, which is assured by a scheduled and thorough maintenance program.

It is not uncommon for the furnace thermocouple to be, for example, at 1700°F/927°C while the work, depending on mass, is 200°F/93°C or more lower. The experienced heat treater looks into the furnace as parts are being heated to ensure that they are coming to heat as uniformly as possible.

Case Microstructure

In a carburized gear, microstructure is extremely important. The desired combination for the case is martensite, austenite, and finely dispersed carbides. This structure must be free of microcracks.

The usual deficiencies are excessive amounts of retained austenite, carbide network, or quenching pearlite, which often is called upper bainite. When it is impractical to cut a gear, specimens as shown in Fig. 5 can be used.

What constitutes excessive amounts of retained austenite is a much debated matter. However, if a case hardness of at least a 58 Rockwell C is obtained, the amount of austenite present usually is not excessive. Still, a case hardness of 60 Rockwell C is preferred. The causes of excessive austenite are one or a combination of the following:

- The steel being used contains too much nickel and/or manganese for the heat treating practice employed.

- Carbon content of the case is excessive, for example, 1.10% in 4820 steel, when 0.8% is adequate.

- Quench is extremely intense.

A reasonably reliable test for excess austenite is to find a gear quite file-hard, but Rockwell C soft, for example, in the low 50s. Parts having excessive retained austenite can be salvaged in more than one way.

If direct-quenched, the parts should be tempered at 500°F/260°C, reheated above the Ac of the core, and requenched. For steels such as 4817 and 4820, a two- to three-minute delay or greater resulting in cooling to 1300°F/704°C to 1350°F/732°C between the hardening furnace and the quench also will reduce the retained austenite.

Another way to salvage a part with exces-

sive retained austenite is to temper the parts at 500°F/260°C and then charge in a carburizing furnace at 1700°F/927°C to decarburize the part surface down to the proper level. After slow cooling, reheat to a temperature 25° to 50° above the Ac of the core and quench.

Because it may substantially reduce the bending fatigue qualities of a gear tooth, low-temperature treating at least down to -100°F and retempering at 325°F/163°C to 350°F/177°C is not a recommended method of reducing retained austenite.

Another important element in carburized case microstructures is the carbide morphology. Network carbide is not permitted due to its weakening and embrittling effects on gear teeth. Carbide network is always the result of excessive case carbon content and/or inadequate hardening in temperature. The condition can only be detected in production by microscopic examination of the carburized surface of a part or a slice from the sample.

The prevention of quenching pearlite, widely called upper bainite or simple bainite, is an additional element in controlling the carburized case microstructure. This constituent is soft, usually 30 to 40 Rockwell C. It also is weak and deleterious to pitting life, as shown in Fig. 6.

Quenching Pearlite

The heat treating operation can be at fault for quenching pearlite formation due to the following:

- Inadequate case carbon content,
- Excessive transfer time from the hardening furnace into the quench,
- Inadequate quench intensity.

To get a steel to harden free of quenching pearlite, it must be cooled fast enough to avoid the "nose" on the IT curves, down to at least the M line; however, M is desired.

The main reason for the presence of quenching pearlite in gears is sluggish quenching. Leading edge heat treating firms avoid this undesirable constituent with vigorous quenching and also reduce steel cost with lower cost alloy.

The extreme importance of preventing quenching pearlite warrants discussion of some steps to be taken in the choice process. Each alloy steel, depending on the case carbon and

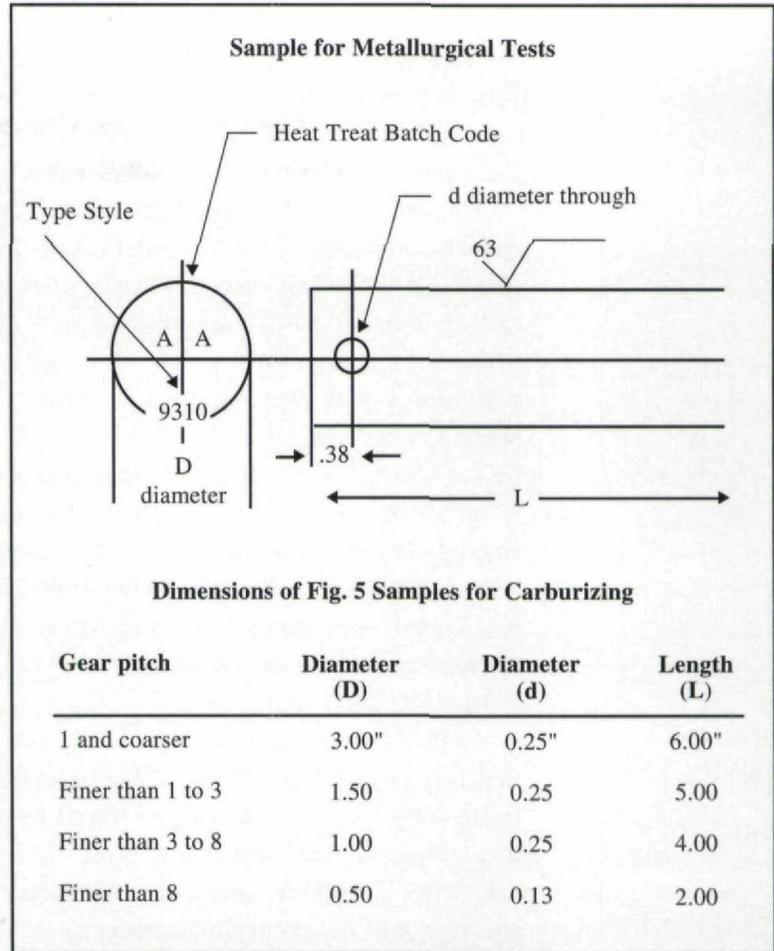


Fig. 5 - When it is economically impractical to cut a gear to check case depth, a heat treater can use a sample design and table of sizes for different size gears.

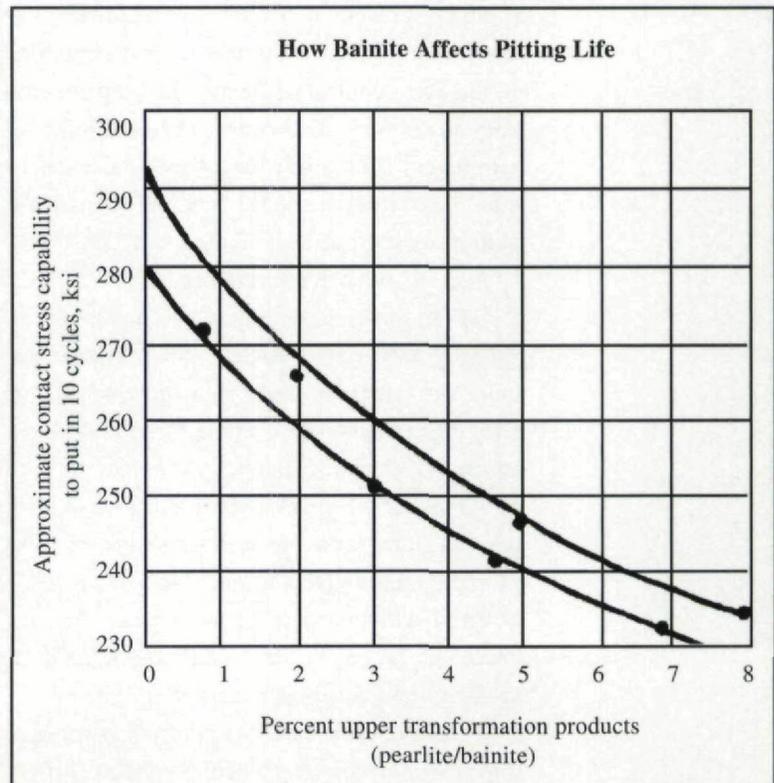


Fig. 6 - Bainite, also call quenching pearlite, is soft, weak, and deleterious to pitting life.

carburizing practice, has a quench-cooling rate in J distance below which quenching pearlite will form. Fig. 7 gives the typical cooling rates, most of which would be greater for a case carbon content less than 1.00% carbon.

For a 4 DP solid pinion, for example, the quench-cooling rate in the root fillet is 6/16"J (0.375). If 1.00% case carbon is to be used by carburizing at 1700°/927°C, cooling to 1500°F/816°C and direct-quenching, only a few steels will harden with freedom from quenching pearlite. They are 3310, 4320, 4620, 4817, EX-24, EX-29, EX-31, 8822, and 94B17. Steels 3310, 9310, and 4817 will contain excessive amount of retained austenite with 1.00% case carbon. If the part is to be carburized to 1.00% case carbon, slow cooled, and then reheated for hardening, these steels will work: 3310, 9310, 4320, and EX-31.

Of the two general types of quenching, the first is a surface layer of quenching pearlite frequently associated with intergranular oxidation and/or partial decarburization. It usually is only 0.0015" to 0.002" maximum thickness, and of no significant engineering effect.

The second type is found as dark patches deep into the surface. If 10 or greater stress-cycle life is required, no quenching pearlite should be present. If 10 cycles are adequate, 3% maximum of quenching pearlite is acceptable.

Positive control of quenching pearlite can only be done by microscopic examination of a sample cut from a gear or a slice of the specimen. Examination should be at 400X to 500X with a two-to four-second etch with 2% Nital.

Microcracking

Microcracking also must be considered in suitable carburizing control. Such cracks are more prevalent in steels in which the major alloying elements are carbide formers, for example, 4120 and 8620.

Case carbon content and quench vigor also play an important role in microcracking. For example, gears 8 DP and finer made from 8617 or 8620 will microcrack, even when reheat-hardened, when the case carbon is 0.90% or greater, and the oil quench is well agitated.

Heat treaters sometimes resort to water or a thin polymer quench to achieve the specified hardness on carburized steels such as 5120 or 8620, but this usually results in severe

microcracks. Microcracks adversely affect bending fatigue life, although it varies with the severity and location of the cracks.

In the case of bending fatigue life of a 8620 steel that was reduced by a factor of 1,000, the problem was solved by going to a 4020 analysis steel — 1018 plus 0.20/0.30% molybdenum. It is best to select material and heat treat processing so there are no microcracks, which is an achievable objective. If a few micro-cracks are found on a single test, the chances are very good that higher side heats will be more severely cracked with significantly shortened lives.

A slice from a sample or from a section of a scrap gear can be used for the microcrack specimen. The etch must be very light, for example, 2% Nital for two seconds. With a more or less normal etch, the microcracks will be invisible.

Although the hardness test is a crude approximation of the metallurgical quality of high quality carburized gears, it should be performed at least once at the specified test location on each part. Preferably a minimum of three tests should be made and the average reported. There is some evidence that the contact stress capability of a carburized gear is a function of its hardness.

The test location is very important, especially on gears 6 DP and coarser. The best locations from a design standpoint are at the LPSTC for contact stress capability and the root fillet for strength.

Coarse pitch gears are troublesome. The case carbon content is highest at the tips of the teeth and decreases along the tooth flank to the root fillet. Also, if the quench is close to being deficient, the tips of the teeth might be hard, but not so with the case at the LPSTC and root fillet, because of the lower carbon and less effective quench mainly due to vapor-pocket formation.

When gears cannot be cut up, there are hardness testers that can nondestructively make pitch line and root fillet tests. Another means of closely estimating the case hardness at the LPSTC or in the root fillet is to test the surface hardness of the metallurgical requirement samples as shown in Fig. 5. Usual case hardness requirements are 58, 59, or 60 Rockwell C minimum with a range of plus 5, 6, or 7 points.

A fast but very discriminating hardness tester is a high-quality file. There is a certain amount

Microstructure Capabilities of Carburizing Steels

Composition ^b	J distance to first bainite ^a			
	Direct-quench ^c		Reheat-quench ^d	
	typical (inches)	estimated minimum (inches)	typical (inches)	estimated minimum (inches)
10B16 (1.00 Mn, 0.17 Cf, 0.07 Mo)	0.138	0.075	0.122	0.062
1018	0.075	0.050	0.055	0.030
10B22 (0.84Mn)	—	0.075	0.105	0.062
15B24 (1.40 Mn)	0.122	0.100	0.116	0.100
1117 (1.27 0.06 Cr)	0.122	0.062	0.116	0.062
1118	—	0.062	—	0.075
1213	0.122	0.062	0.118	0.062
1524	—	0.100	—	0.100
3310	2.000+	2.000	2.000+	2.000
4118	—	0.062	0.085	0.075
4120 (0.8 Mn, 1.00 Cr, 0.05 Ni, 0.25 Mo)	—	0.075	0.114	0.100
41B16	—	0.100	0.186	0.125
4320	0.960	0.875	—	0.875
4620 (with 0.40 Mo)	—	1.250	0.250	0.200
4620	—	0.750	0.272	0.250
4817	2.000+	2.000	2.000+	2.000
5120	—	0.050	0.080	0.062
8620	0.232	0.200	0.108	0.100
8720	—	0.300	0.132	0.100
8822 (low side)	—	0.750	0.189	0.185
8822 (medium composition)	1.270	1.000	0.300	0.250
X9115	—	0.075	0.104	0.075
9120	—	0.075	0.084	0.075
94B17	—	0.500	0.173	0.150
EX-15 (1.00 Mn, 0.50 Cr, 0.16 Mo)	—	0.200	0.116	0.100
EX-24 (0.87 Mn, 0.55 Cr, 0.25 Mo)	0.385	0.300	—	0.200
EX-29 (0.87 Mn, 0.55 Cr, 0.35 Mo, 0.55 Ni)	0.760	0.750	—	0.300
EX-31 (0.80 Mn, 0.55 Cr, 0.35 Mo, 0.85 Ni)	2.000	2.000	—	2.000
20 Mn Cr4	0.375	0.285	0.188	0.100
16 Mn Cr5	0.375	0.250	0.188	0.150

^a In inches at 1.00%.
^b Composition given for nonstandard and experimental steels only.
^c Direct-quench consists of carburizing at 170°F, cooling to 1550°, and quenching.
^d Reheat hardening consists of carburizing at 1700°F, slow cooling to room temperature, reheating to 1550°F, and quenching. No tempers.

Source: Climax Molybdenum Co.

Fig. 7 - Each alloy steel, depending on case carbon and carburizing practice, has a quench cooling rate in J distance below which quenching pearlite forms. Listed above are typical cooling rates, most of which would be greater for a case carbon content less than 1%.

of art required to run the test, but generally it consists of just laying a file on the surface to be tested, applying a moderate amount of downward pressure, and then moving the file slightly forward. If the file "bites," the hardness is questionable. If another application of the file to the same area removes metal, the surface is file-soft. This test will detect partial decarburization and structures with quenching pearlite. ■

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